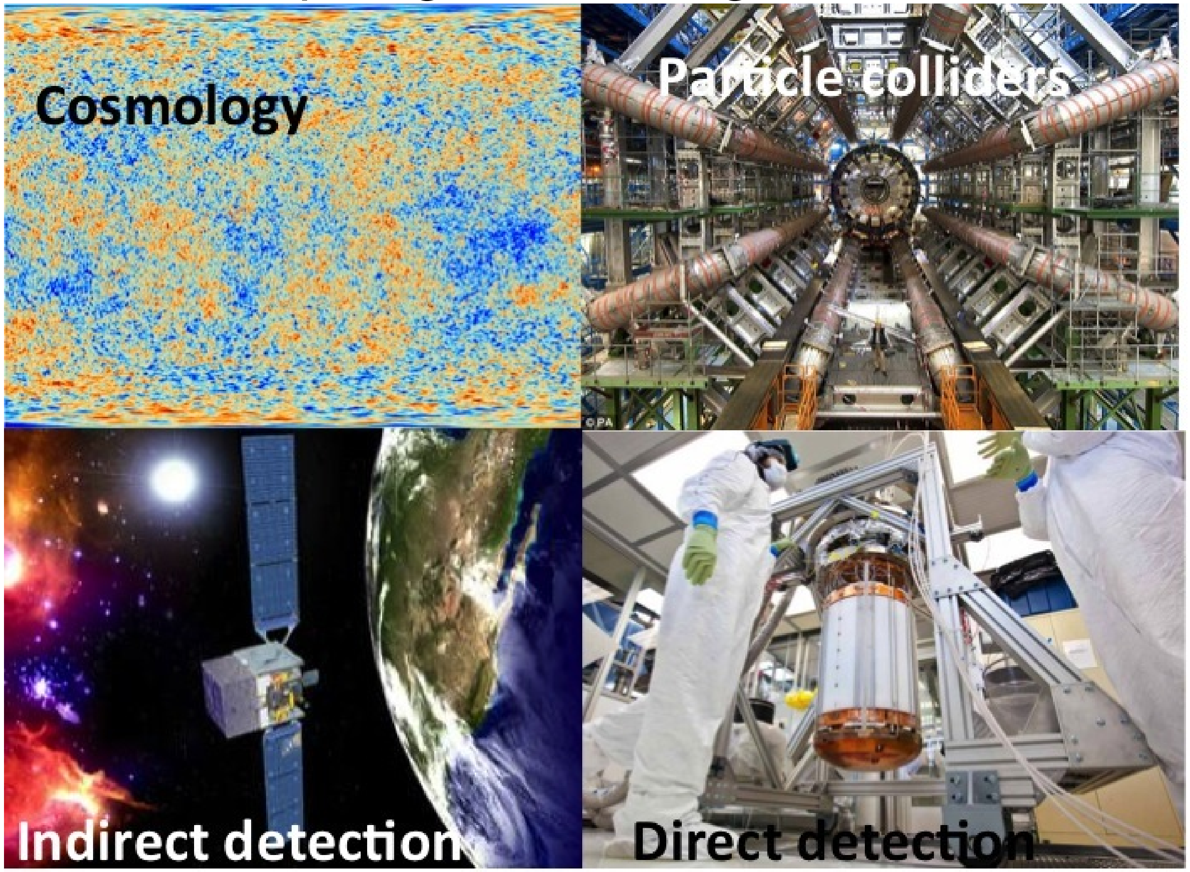
Direct Detection and Collider Searches of Dark Matter Lecture 1

Graciela Gelmini - UCLA

Dark Matter School, Lund, Sept. 26-30, 2016

The hunt for Dark Matter, the most abundant form of matter in the Universe is multi-pronged involving ...



Content:

- What we are looking for
- Overview of what we know and do not know about Dark Matter (DM) and possible DM constituents
- DM particles as the earliest relics (from the pre Big-Bang Nucleosynthesis era)
- Sterile neutrino DM observed?

Subject is very vast, so idiosyncratic choice of subjects + citations disclaimer

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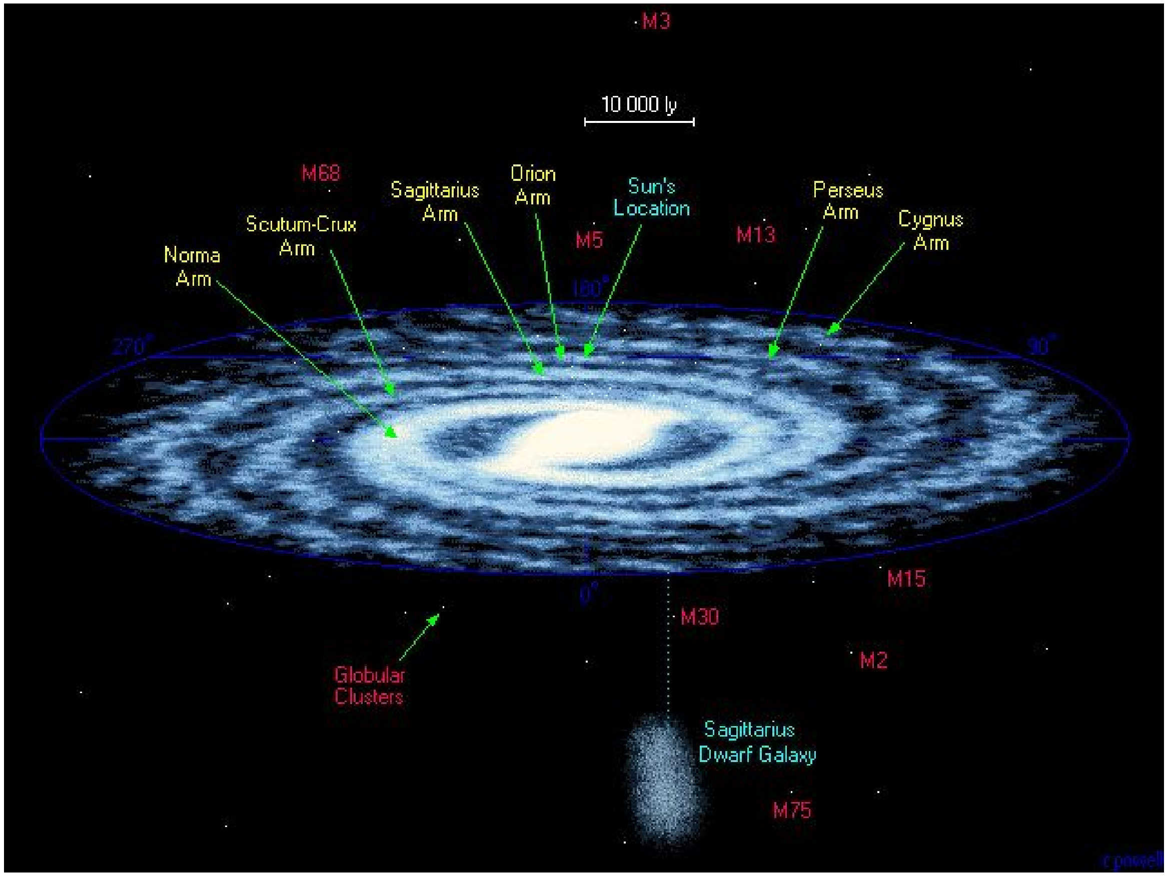
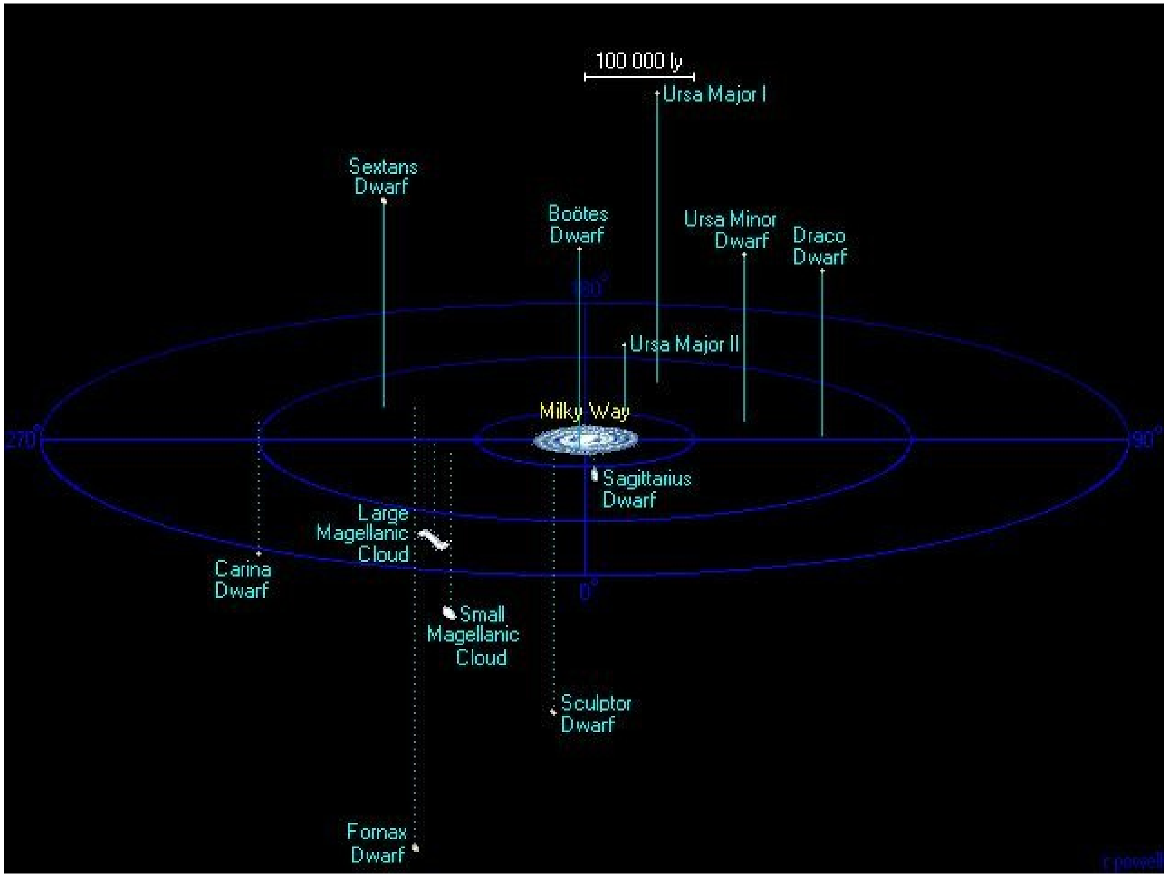
What we are looking for

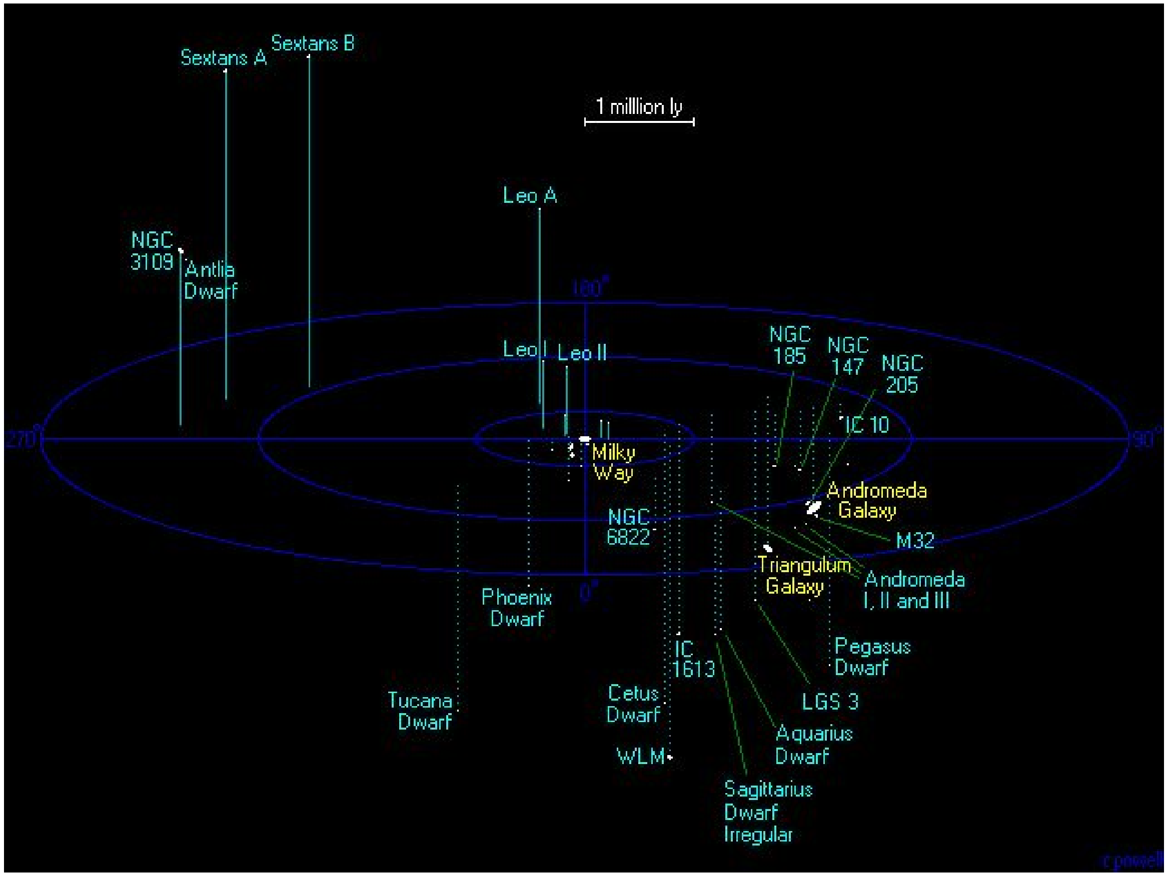
The Universe around us: Galaxies are the building blocks of the Universe. The Milky Way and the Sagittarius Dwarf galaxy its nearest satellite galaxy



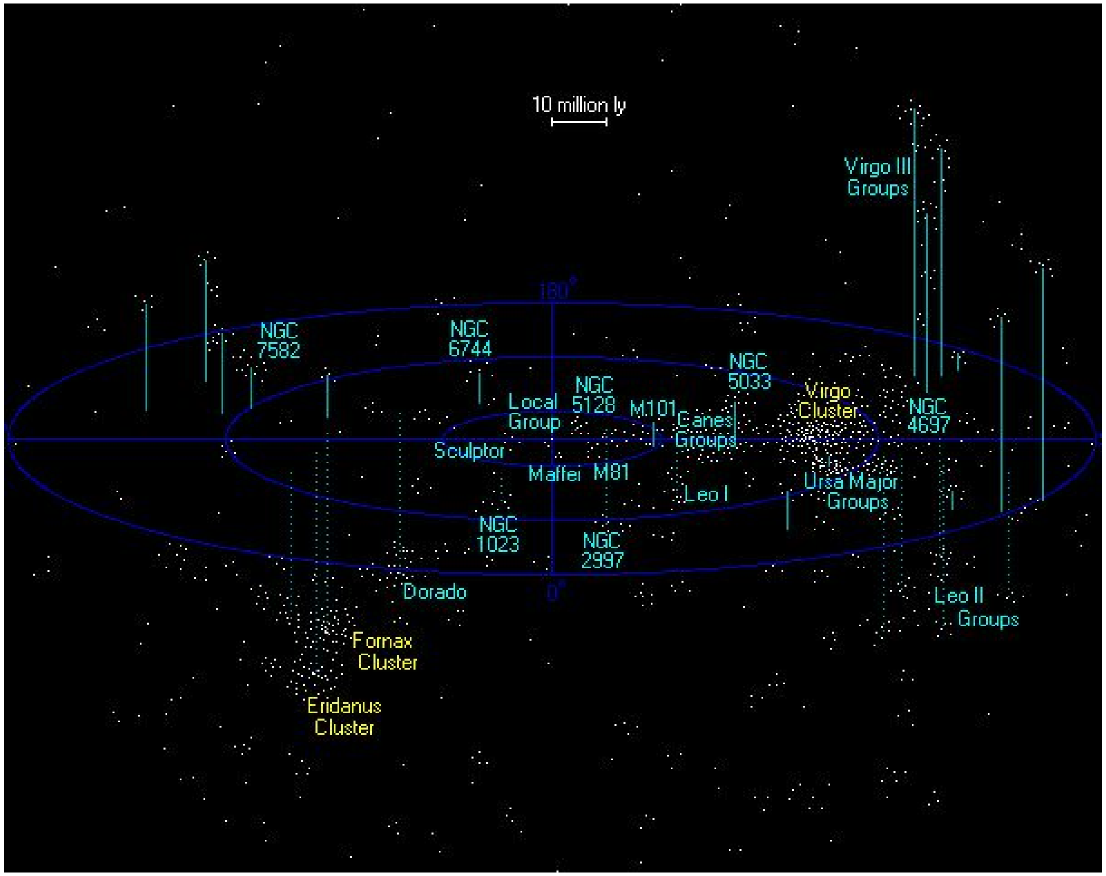
The Milky Way has many small satellite galaxies 55 dwarf galaxies have been found so far (23 in 2015, 3 in 2016)



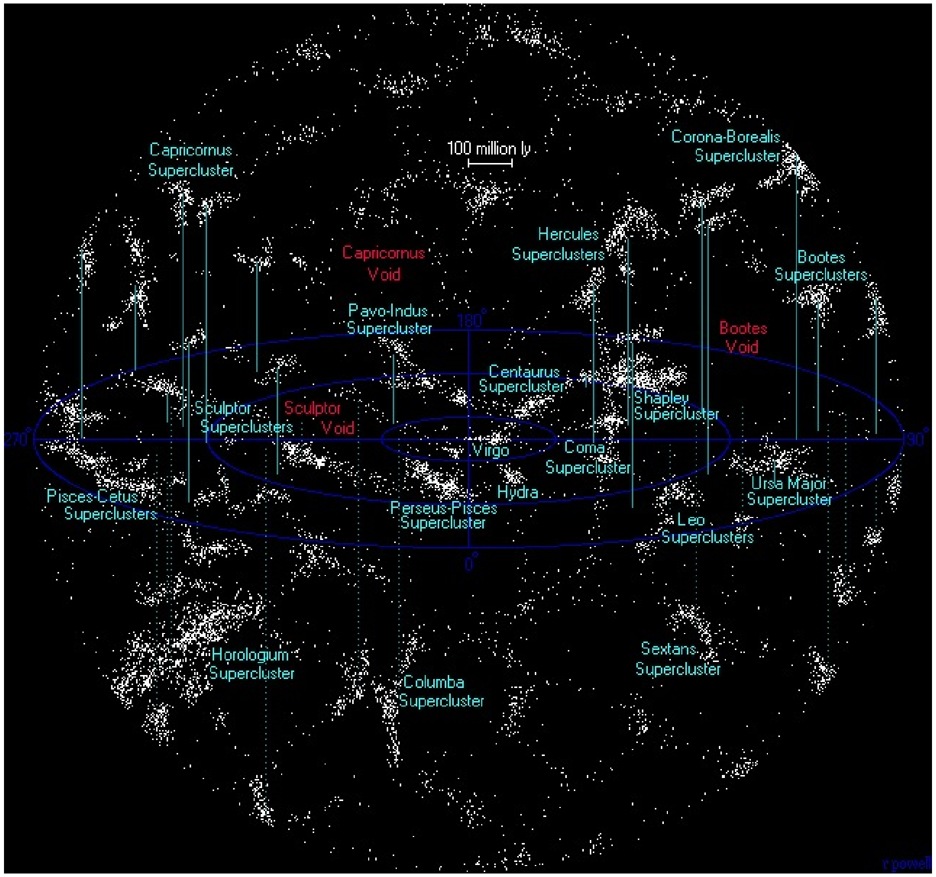
Galaxies come in groups, clusters, superclusters......Our Local Group of galaxies



Galaxies come in groups, clusters, superclusters...... Our Local Group of galaxies is in the outskirts of the Virgo Cluster



Galaxies are the building block of the Universe: they come in groups, clusters, (which form "filaments, walls and voids")



The DARK MATTER problem has been with us since 1930's,

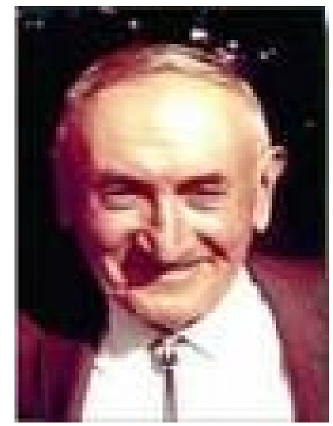
name used by Fritz Zwicky in Helvetica Physica Acta Vol6 p.110-127, 1933

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.



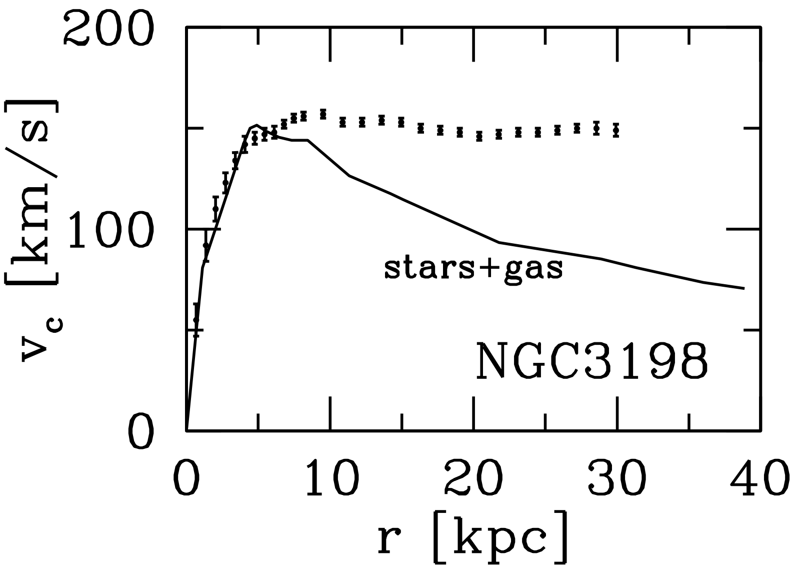
On page 122

gr/cm³. Es ist natürlich möglich, dass leuchtende plus **dunkle (kalte) Materie** zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\varrho \sim 10^{-28}$ gr/cm³ erscheint daher nicht

Used the Virial theorem in the Coma Cluster: found its galaxies move too fast to remain bounded by the visible mass only. J. Ostriker: in the first 40y his seminal 1937 paper had 10 citations!

Dark Matter rediscovered

In 1970's: Vera Rubin and others found rotation curves of galaxies ARE FLAT!



$$\frac{GMm}{r^2} = m\frac{v^2}{r} \Rightarrow v = \sqrt{\frac{GM(r)}{r}}$$

$$v = const. \Rightarrow M(r) \sim r$$

even where there is no light!

1 pc = 3.2 ℓy

Dark Matter dominates in galaxies e.g. in NGC3198

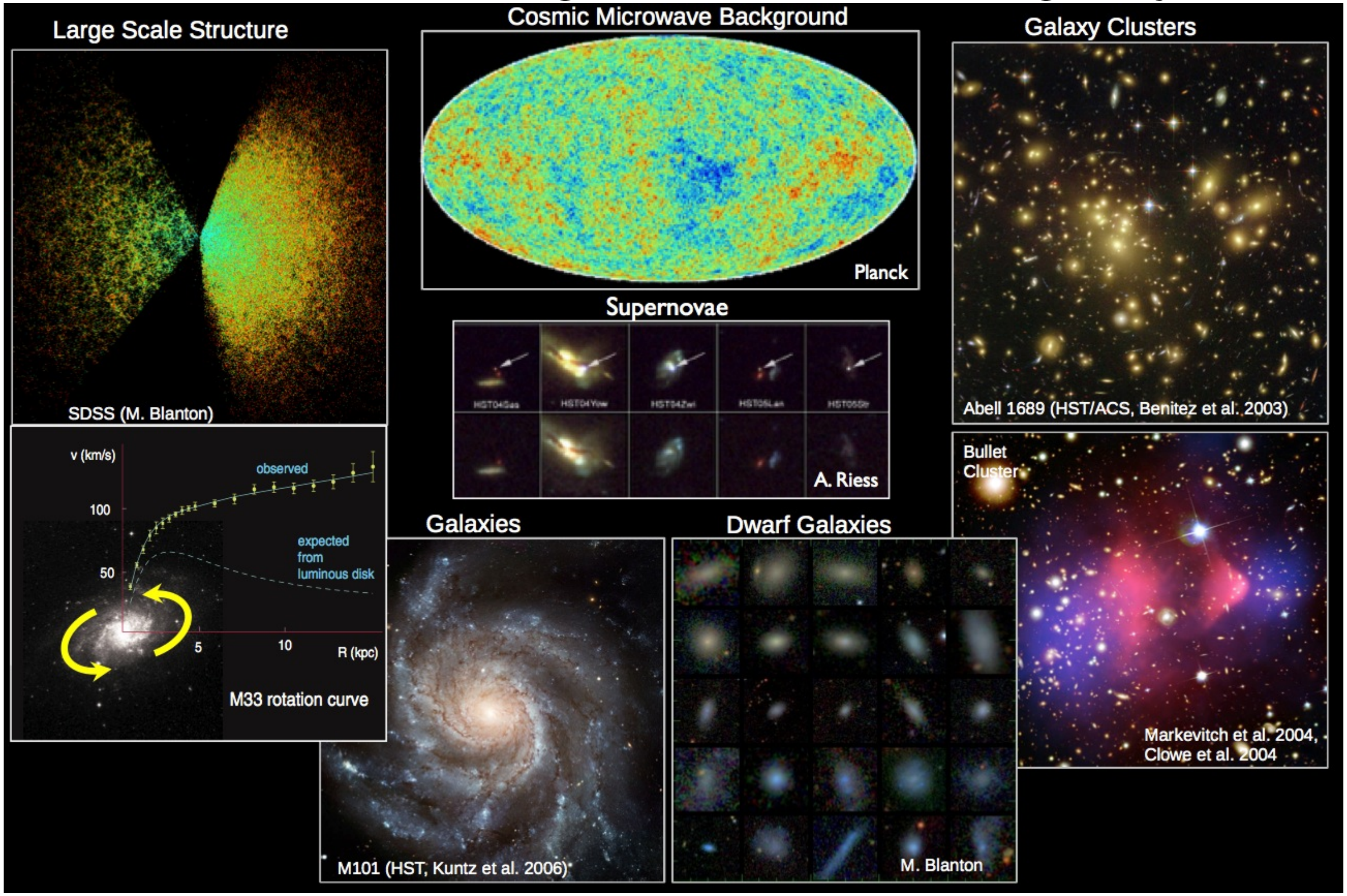
$$M = 1.6 \times 10^{11} M_{\odot}(r/30 \text{ kpc})$$

$$M_{stars+gas} = 0.4 \times 10^{11} M_{\odot}$$

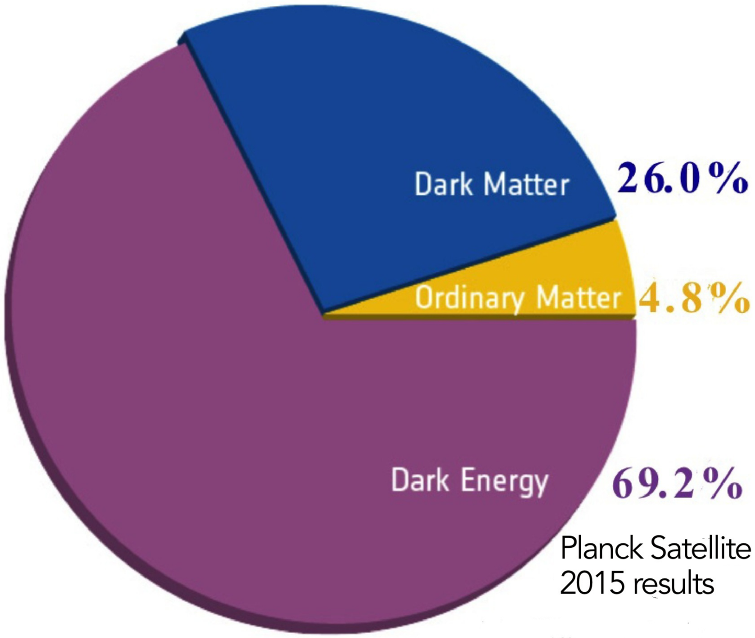
$$\frac{M}{M_{vis}} > 4$$

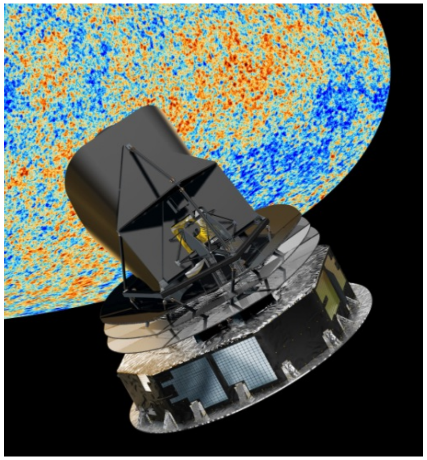
We are going to concentrate on the DM in the Dark Halo of our own galaxy

By now evidence for "missing mass" from dwarf galaxy scales on



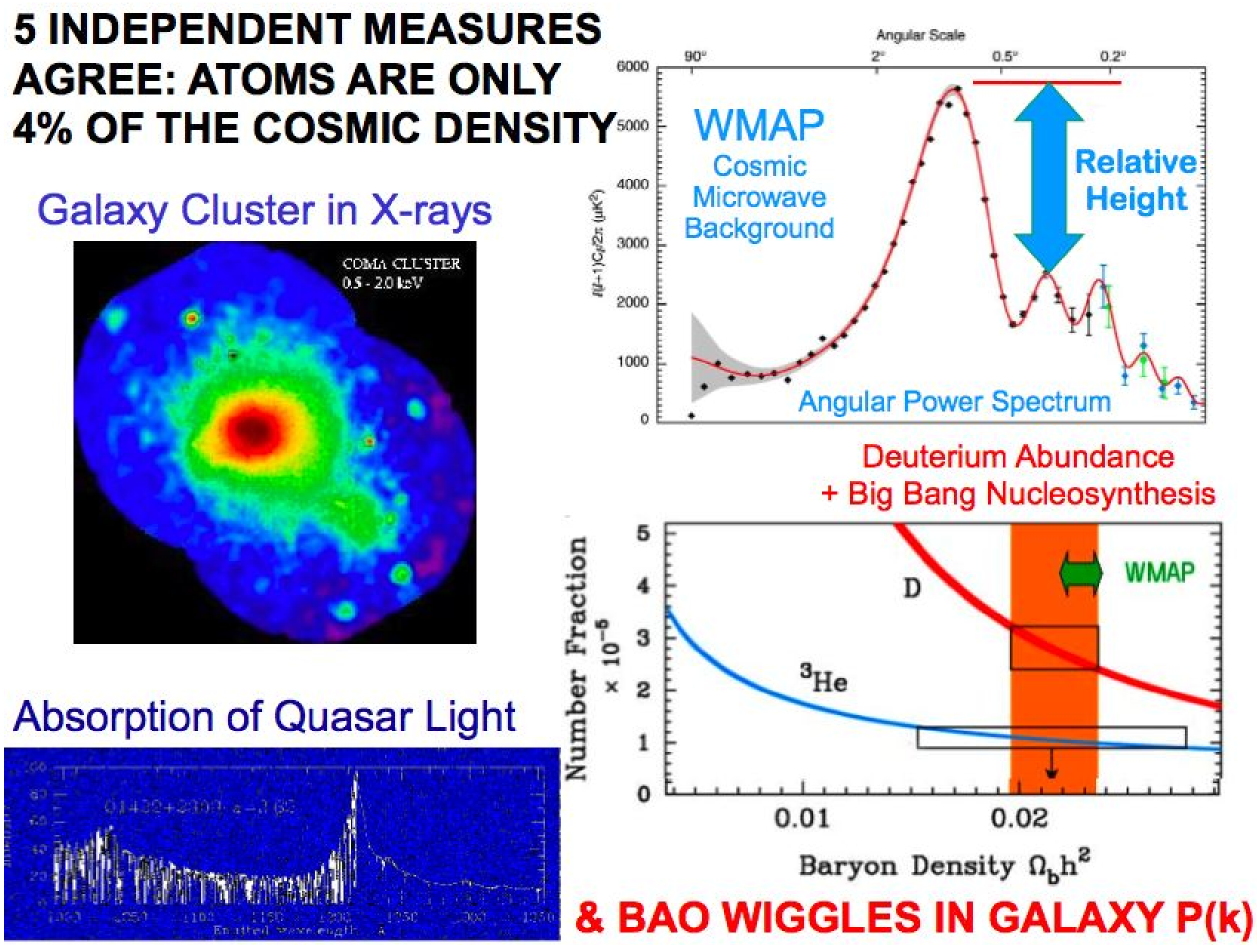
At the largest scales: the "Double-Dark" model





"DARK ENERGY" 69%(with repulsive gravitational interactions)
"MATTER" 31% (with usual attractive gravitational interactions- forms gravitational bound objects) and most of it is **"DARK MATTER" 26%**

Our type of matter is only $< 5\%$.... Fig: from J. Primack 2010



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What we know about dark matter

After 80 years, what we know about DM:

- **1- Has attractive gravitational interactions and is stable (or has a lifetime $>> t_U$)**

  We have no evidence that DM has any other interaction but gravity. Could departures from the law of gravity itself explain the data instead of DM?

- **2-MOND (Modified Newtonian Dynamics) and covariant extensions with only visible matter are not enough at scales larger than galactic** some kind of extra matter is necessary (so still DM!). Do no explain consistently all the data as DM does.

After 80 years, what we know about DM:

- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- DM and not [MOND + only visible matter]**
- **3- DM is not observed to interact with light** i.e. it is either neutral or with a very small electromagnetic coupling such as:

  "Milli-Charged DM" which can be part of "Atomic DM", with dark protons and dark electrons forming dark atoms or "Mirror DM" whose Lagrangian is a copy of that of the SM, but for the mirror particles,

  or "electric or magnetic dipole DM", or"anapole DM"

- **4- The bulk of the DM must be nearly dissipationless, but part of it could be dissipative.** i.e. cannot cool by radiating as baryons do to form disks in the center of galaxies. Otherwise, their extended dark halos would not exist.

  But $< 10\%$ could be (radiating "dark photons" or other light dark particles): "Double Disk DM" (DDDM) Fan, Katz, Randall & Reece 1303.1521-1303.3271

  A Dark Disk was shown to arise in some simulations of galaxy formation including baryonic matter besides the usual non-dissipative Cold DM, but with dissipative DM it should be a pervasive feature of all disk galaxies

  (and even "kill the dinosaurs"?! Randall& Reece arXiv:1403.0576 proposed that the Dark Disk is inclined with respect to the visible disk and periodic extensions happen when the solar system passes through it)

After 80 years, what we know about DM:

- **1- Attractive gravitational interactions and lifetime $>> t_U$**
- **2- DM and not [MOND + only visible matter]**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless, but ≤10% of it could be dissipative.**
- **5- The mass of the major component of the DM has only been constrained within some 80 orders of magnitude!**

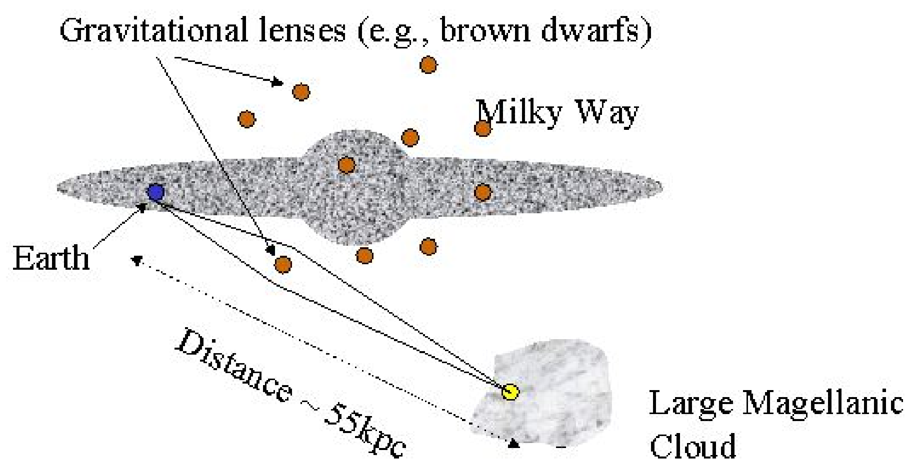
  10^{-31} GeV ≤ **mass** ≤ $2\times10^{-9}M_{\odot}$ =2 $\times10^{48}$GeV

Limits on MACHOS (Massive Astrophysical Compact Halo ObjectS):

Cannot be the bulk of the DM if **mass** $\geq 2 \times 10^{-9} M_{\odot} \simeq 2 \times 10^{48}$GeV

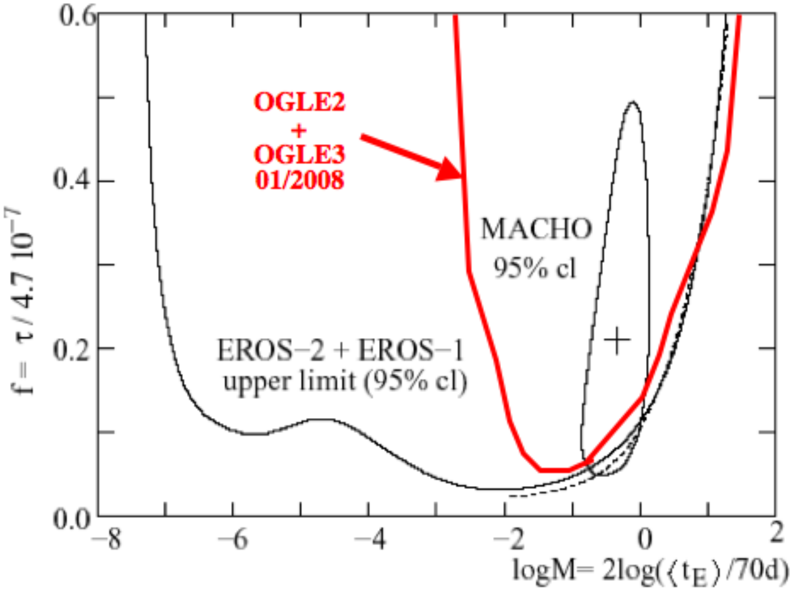
MACHO and EROS collaborations 2009 M. Moniez arXiv:0901.0985 [astro-ph.GA], Griest, Cieplak and Lehner 1307.5798

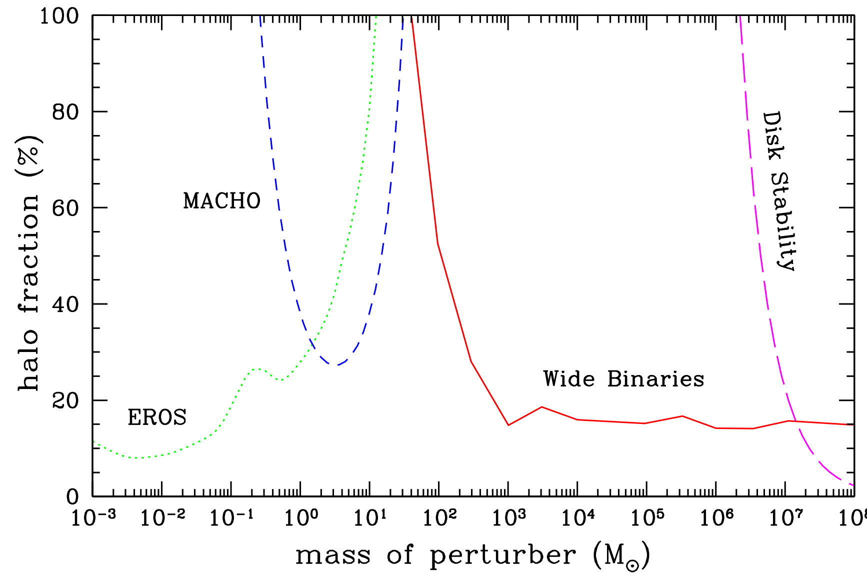
Searched for using gravitational "microlensing" of stars in satellite galaxies and the Galactic Center: multiple images are superposed producing an "anti-eclipse" (star becomes brighter for a while).



Dark Matter: not MACHOS

M. Moniez arXiv:0901.0985 [astro-ph.GA] Combined with older results for larger masses: Yoo, Chaname, Gould, ApJ**601**, 311, 2004 Griest, Cieplak and Lehner 1307.5798





2009 limit: $m > 10^{-7}$ $M_\odot$ cannot be the bulk of the DM ($M_\odot = 10^{57}$GeV)

2013 limit: (using Kepler satellite data) $m >$2 10^{-9} $M_\odot$ cannot either.

Notice, possible window 20 $M_\odot < m <$100 $M_\odot$? (LIGO $M_{BH} \simeq 30 M_\odot$)

Problem with MACHOS: how would they form? Could be Primordial Black Holes but limits constrain them to be only a fraction of the DM for almost any mass.

Dark Matter: could be Primordial Black Holes (PBH)?

PBH are a hypothetical type of black hole not formed by the gravitational collapse of a large star but in an early phase transition Carr and Hawking, 1974

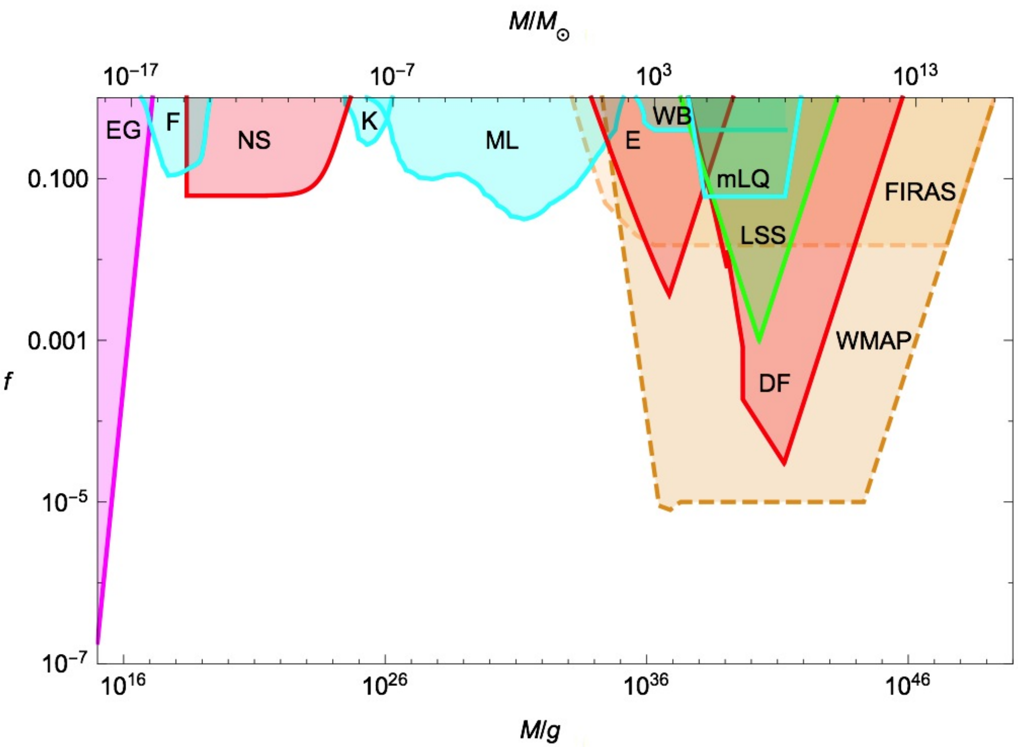
Many limits exclusively applying to BH:

- $m_{PHB} > 10^{15}$g $= 6 \times 10^{38}$ GeV lighter would have evaporated by now
- $m_{PHB} > 10^{17}$g or evaporating BH would have been observed (by EGRET and Fermi)
- 5 10^{17}g$< m_{PHB} < 10^{20}$g excluded by non-observation of "femtolensing" of GRB 1204.2056
- 10^{16}g$< m_{PHB} < 10^{22}$g excluded- its accretion in stars would destroy compact remanent 1209.6021
- 3 10^{18}g$<m_{PHB}<$ 5 10^{24}g excluded- its accretion in n stars in GC would destroy them 1301.4984
- $m >$ $M_{\odot}$= 2 10^{33}g excluded by absence of CMB spectral distortions 0709.0524

Dark Matter: could be Primordial Black Holes (PBH)?

compilation of bounds on density fraction f

Carr, Kuhnel and Sandstad 1607.06077



Only narrow windows might remain for PBH weakening some constraints, e.g.

just below the MACHO microlensing limit 4 10^{24}g=2 $10^{-9}M_\odot$

or in MACHO "window" 20 $M_\odot$-100 $M_\odot$ between microlensing and wide binaries disruption limits

(e.g. if PBH are small at CMB emission and merge very efficiently) Clesse&Garcia-Bellido 1501.07565

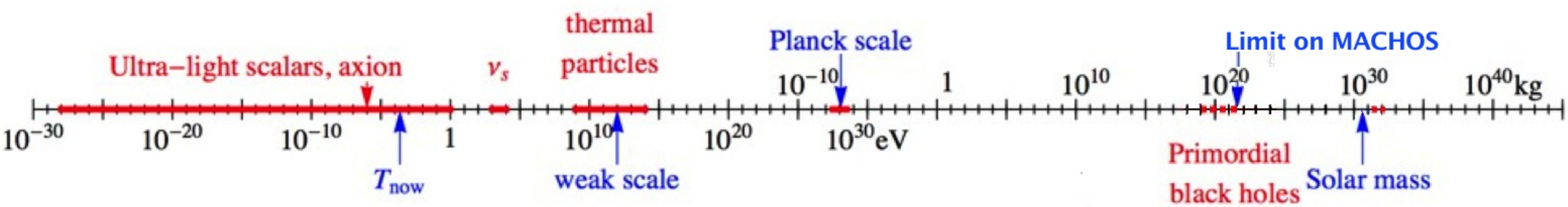
Could LIGO BH $\sim 30M_\odot$ be most of the DM? Bird etal. 1603.00464, Clesse&Garcia-Bellido 1603.05234

- **5- The mass of the major component of the DM has only been constrained within some 80 orders of magnitude.**

$$10^{-31}\ \text{GeV} \leq \textbf{mass} \leq 2{\times}10^{-9}M_\odot = 2\ 10^{48}\text{GeV} = 4\ 10^{21}\text{kg}$$

Lower limit: "Fuzzy DM", boson with de Broglie wavelength 1 kpc Hu, Barkana, Gruzinov, 2000 or 0.2-$0.7\ \times 10^{-6}$ GeV $\leq$ **mass** for particles which reached equilibrium - depending on boson-fermion and d.o.f. (*) Tremaine-Gunn 1979; Madsen, astro-ph/0006074

(* You will compute the "Fuzzy DM" and Tremaine-Gunn limits as an exercise)



The limits just presented, and the fact that particle candidates can have the right relic abundance to be the DM, constitute the only observational arguments we have in favor of DM elementary particles candidates.

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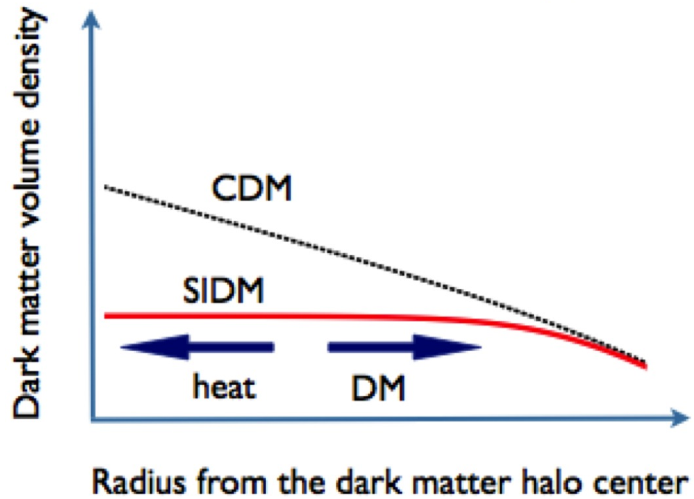
- **4- The bulk of the DM must be nearly dissipationless, but ≤10% of it could be dissipative.**
- **5- Mass within some 80 orders of magnitude.**
- **6- DM has been mostly assumed to be collisionless, however the upper limit on DM self-interactions is huge**

Bullet cluster + non-sphericity of galaxy and cluster halos
$\boldsymbol{\sigma_{self}/m} \leq 1$ cm^2/g $= 2$ barn/GeV $= 2\times10^{-24}$ cm^2/ GeV
by comparison e.g. ^{235}U-neutron capture cross section is a few barns!
Self Interacting DM (SIDM) just below limit Would also erase small scale structure

(Limit on σ_{self}/m ratio comes from requiring self-interaction mean free path $\lambda_{mfp} \simeq 1/n\sigma_{self} = m/\rho\sigma_{self}$ be long enough, $n = \rho/m$ is the DM number density)

Self Interacting DM (SIDM) would also erase small scale structure and flatten out the central regions of dwarf galaxies (forming a core)



Having a large self interaction at smaller scales and a negligible one at large scales points to light mediators φ (*)

(Feng, Kaplinghat& Yu 2009,

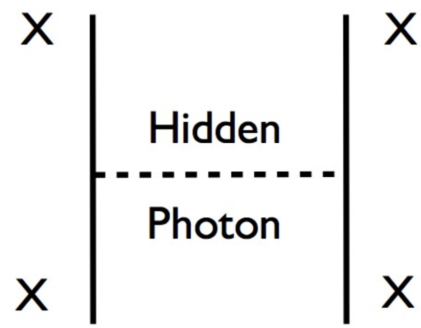
Buckley& Fox (2009),

Loeb&Weiner (2010),

Tulin, Yu& Zurek 2012, 2013...)

$$\sigma \sim \frac{\alpha_X^2}{m_X^2 v^4}$$

$m_X v >> m_\phi$



(*) You have an exercise to see why

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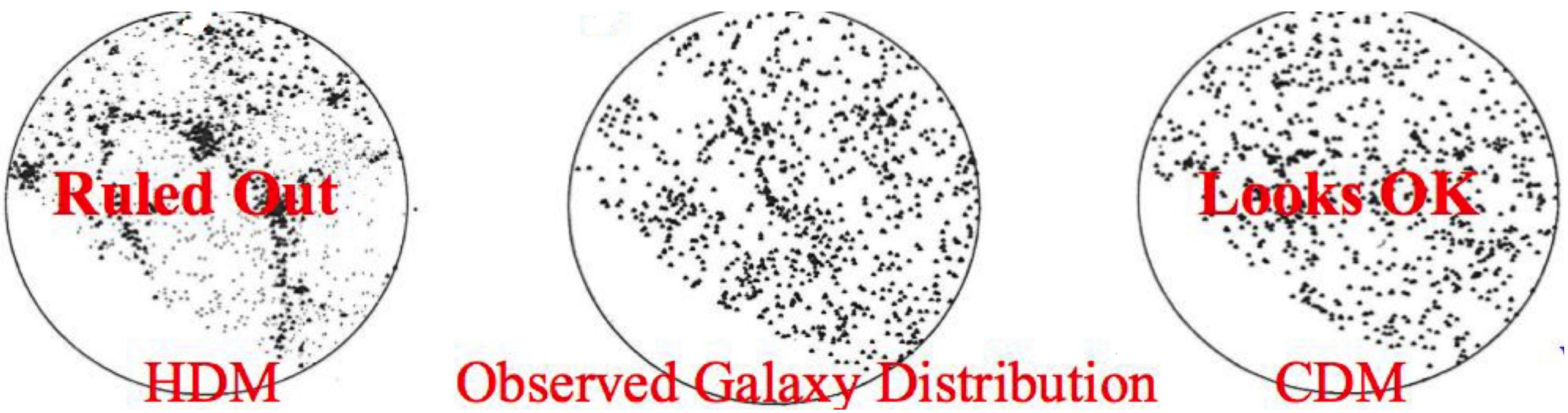
- 6- DM has been mostly assumed to be collisionless, but huge self interaction upper limit $\sigma_{\rm self}/{\rm m} \leq 2$ barn/GeV
- 7- The bulk of the DM is Cold or Warm, thus particle DM requires BSM physics

Dark Matter is "Cold" or "Warm"

Dark Matter is classified as "HOT" or "WARM" of "COLD" if it is

RELATIVISTIC (moves with c), SEMI-RELATIVISTIC or NON-RELATIVISTIC

at the moment dwarf galaxy core size structures start to form (when $T \sim 1keV$).



"Double-Dark" model works well with CDM or WDM above galactic scales, distinction at sub-galactic scales

Fig: from Tegmark ("Standard model" with ΛCDM: with Cold DM)

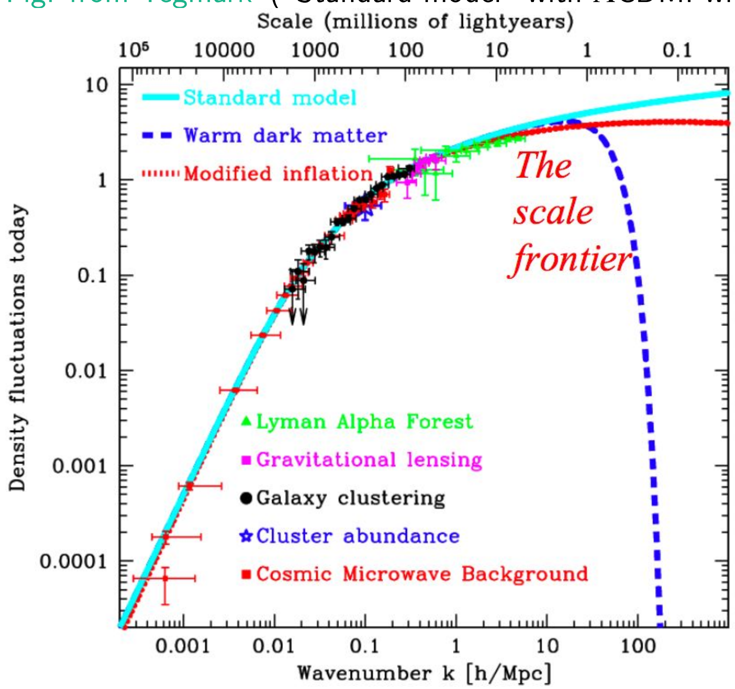
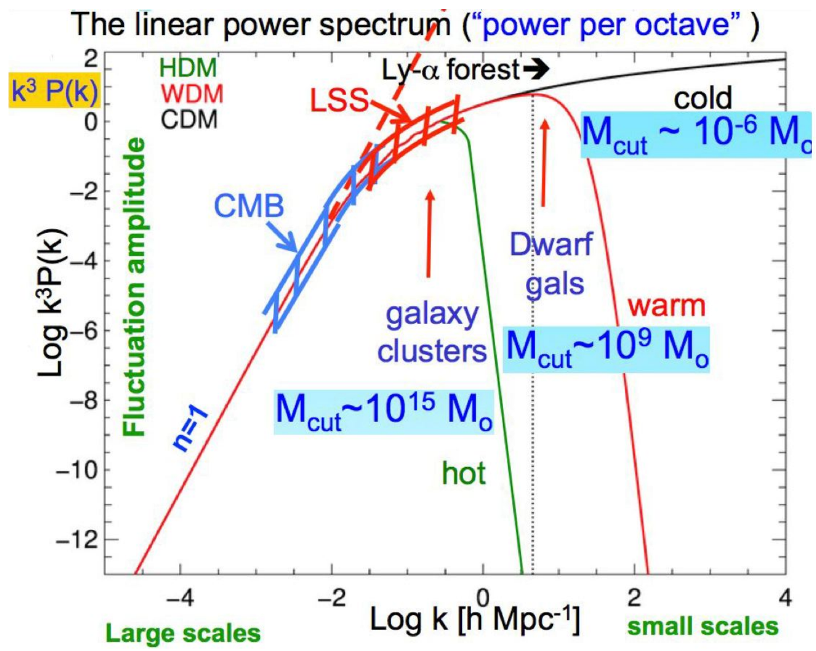


Fig: from Carlos Frenk



Distinguishing CDM-WDM-SIDM-mixed DM and baryonic effects at sub-galactic scales is where most of the structure formation simulations and observational efforts are directed at present.

No CDM or WDM particle candidate in the SM!

In the SM only **neutrinos** are part of the DM- they are light m< eV and in equilibrium until BBN, $T \simeq 1$ MeV thus they are **Hot DM (HDM)**

But many in extensions of the SM!

Warm dark matter (WDM):

- sterile neutrino, gravitino, non-thermal WIMPs...

Cold dark matter (CDM):

- WIMPs, axions, gravitinos, WIMPZILLAs, solitons (Q-balls) and many more...

(WIMPs, Weakly Interacting Massive Particles
but wimp = a weak, cowardly, or ineffectual person *(Merriam-Webster Dictionary)*)

Particle DM requires new physics beyond the SM!

DM particle candidates require BSM physics

starting from those requiring the smallest modification of the Standard Model.
- sterile neutrinos
- axions
- WIMPs, superWIMPs, ALPs, WISPs...

Either BSM models produced by reasons other than the DM e.g. Supersymmetric models Technicolor models "Little Higgs" models, Inert Doublet models, which provide the main potential discoveries at the LHC and also DM candidates . . . LSP, Lightest Technibaryon, LKP (Lightest KK Particle) or LZP (in Warped SO(10) with Z3), LTP (Lightest T-odd heavy γ in Little Higgs with T-parity), LIP...

- Or "Boutique models" produced largely ad-hoc to try to explain DM hints in direct or indirect DM searches or SIDM or dissipative DM....Made to be DM-not to solve any SM problem may provide novel signatures for the LHC- e.g.entire dark sectors communicating with the SM sector via a "portal" i.e. a small coupling to one type of SM particle (photons and Z's, the Higgs boson, neutrinos)

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- **7- The bulk of the DM is Cold or Warm, thus particle DM requires physics beyond the SM**
- **8- Most DM candidates are relics from the pre-BBN era, from which we have no data.** The computation of the relic abundance and velocity distribution of particle DM candidates produced before $T \simeq 4$ MeV depends on assumptions made regarding the thermal history of the Universe.

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DM particles as the earliest relics, from the pre-BBN era

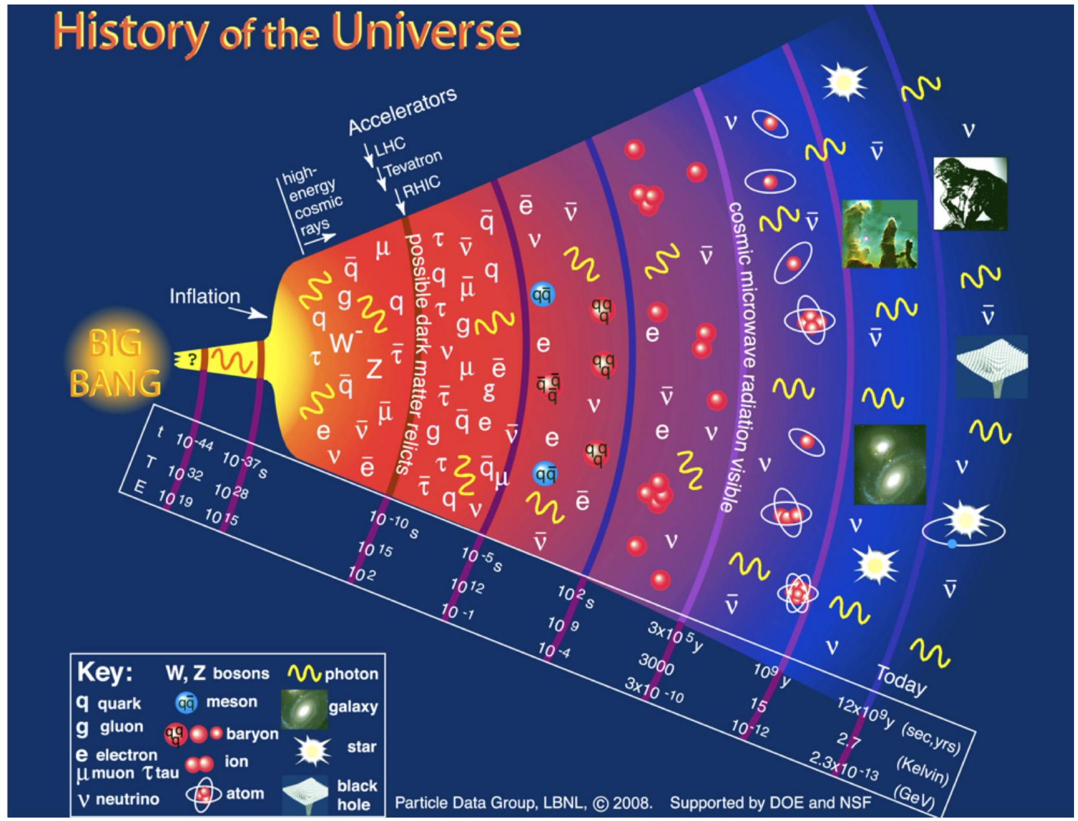
All data confirm the Big-Bang Model of a hot early Universe expanding adiabatically (so T decreases inversely to the size of the Universe)

Earliest data (D, ^{4}He and ^{7}Li):
BBN (Big-Bang Nucleosynthesis)
t≃3-20min T≃MeV (blue line)

Radiation domination to Matter domination
t≃100kyr T≃3 eV

CMB emitted (atoms form)
(Cosmic Microwave Background)
t≃380kyr T≃eV

Now (Planck + other)
t=13.798± 0.037×10^{9}ys



Before BBN?

INFLATION?

period of exponential expansion $a \sim e^{Ht}$

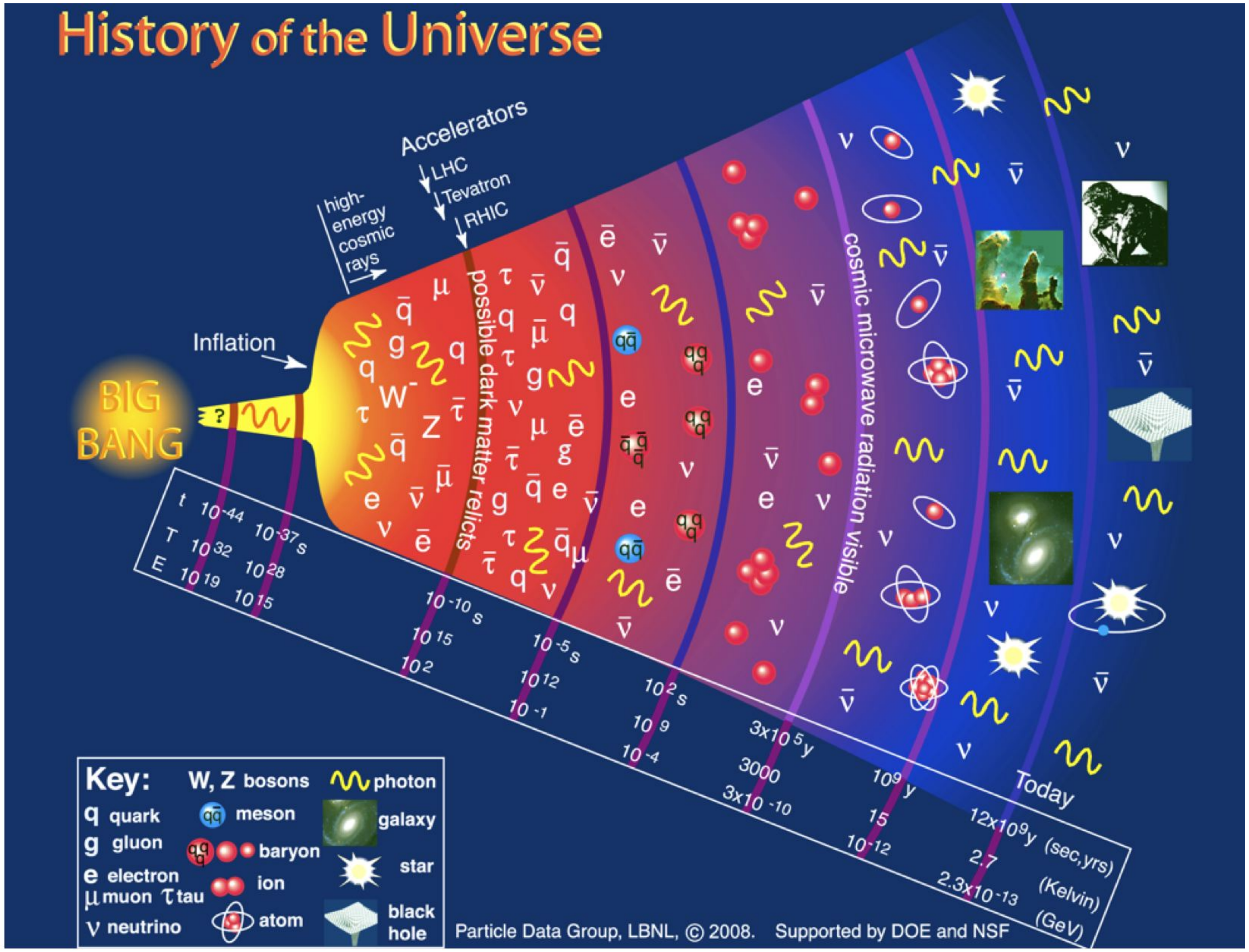
After "reheating", finishes in a Radiation Dominated Universe with temperature

$$T_{RH} > 4 \text{ MeV}$$

expanding adiabatically

$$a \sim 1/T \sim t^{1/2}$$

(even the measurement of gravity waves from inflation would not change this T_{RH} limit)



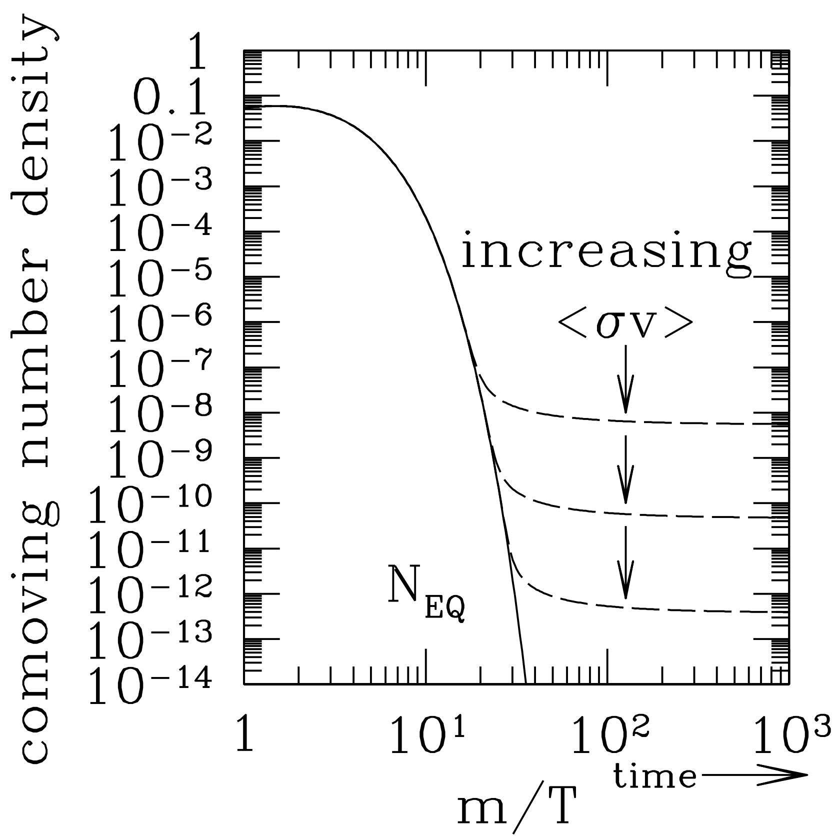
Example: Thermal WIMPs as Dark Matter

Standard calculations: start at $T > T_{f.o.} \simeq m_\chi/20$ and assume that

- WIMPs reach equilibrium while Universe is radiation dominated , $n \sim e^{-m/T}$
- No particle asymmetry
- Chemical decoupling (freeze-out) when $t_{ann} = (\langle \sigma v \rangle\, n)^{-1} \geq t_U \sim H^{-1}$
- No entropy change in matter+radiation

$$\Omega_{std} h^2 \approx \frac{0.2 \times 10^{-9} GeV^{-2}}{\langle \sigma v \rangle}$$

Weak annihilation cross section $\sigma_{annih} \simeq G_F^2 T^2 \simeq 10^{-9} GeV^{-2}$ is enough to get $\Omega_{DM} h^2 \simeq 0.1$! "WIMP Miracle"!



So far we only know that the highest temperature of the most recent radiation dominated epoch of the Universe must be ≥ 4 MeV

Hannestad, 2004

but $T_{f.o.} \simeq m_\chi/20 \geq 4$ MeV for $m_\chi \geq 80$ MeV. For these "thermal" WIMPs, and many other DM candidates whose number density if fixed before $T \simeq 4$ MeV

To compute their relic density we must make assumptions about the pre-BBN epoch.

The standard assumption is that the Universe was radiation dominated up to very high temperatures

There are non-standard cosmological models in which the relic density and momentum distribution of pre-BBN remnants can be very different than in the standard cosmology.

How to get a non-std abundance in non-std cosmologies

- **Increase** the density by increasing the expansion rate at freese-out [e.g. quintessence-scalar-tensor models] or by creating DM particles from particle (or topological defects) decays [non-thermal production].

- **Decrease** the density by reducing the expansion rate at freese-out [e.g. scalar-tensor models], by reducing the rate of thermal production [low reheating temperature] or by producing radiation after freeze out [entropy dilution].

Non-std scenarios are more complicated (baryon number generation, for example) and less studied than the standard

Relic DM particle density as cosmology probe

The relic DM density and relic velocity distribution may be used to find out about the cosmology before BBN. This is not a new idea

Thermal relics: Do we know their abundances?

Marc Kamionkowski and Michael S. Turner
Physics Department, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433
and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500
(Received 25 May 1990)

The relic abundance of a particle species that was once in thermal equilibrium in the expanding Universe depends upon a competition between the annihilation rate of the species and the expansion rate of the Universe. Assuming that the Universe is radiation dominated at early times the relic abundance is easy to compute and well known. At times earlier than about 1 sec after the bang there is little or no evidence that the Universe *had* to be radiation dominated, although that is the simplest—and standard—assumption. Because early-Universe relics are of such importance both to particle physics and to cosmology, we consider in detail three nonstandard possibilities for the Universe at the time a species' abundance froze in: energy density dominated by shear (i.e., anisotropic expansion), energy density dominated by some other nonrelativistic species, and energy densi-

Relic DM particle density as cosmology probe

The relic DM density and relic velocity distribution may be used to find out about the cosmology before BBN. This is not a new idea

MASSIVE PARTICLES AS A PROBE OF THE EARLY UNIVERSE

John D. BARROW

Astronomy Centre, University of Sussex, Brighton BN1 9QH, UK

Received 29 January 1982
(Revised 30 March 1982)

The survival density of stable massive particles with general annihilation cross section is calculated in a cosmological model that expands anisotropically in its early stages ($t < 1$ s). It is shown that the faster average expansion rate leaves a larger present density of surviving particles than in a model that expands isotropically. This allows particle survival calculations to be employed as a probe of the dynamics of the early universe prior to nucleosynthesis. Several examples of heavy lepton, nucleon and monopole survival are discussed.

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Sterile neutrino Dark Matter

Sterile Neutrino DM

The SM has 3 neutrinos with different "flavors", and they are MASSLESS

"Neutrino flavor oscillation": similar to beating of sound of two tones very close in pitch. In quantum mechanics energy E plays the role of the pitch in sound, and a small difference in E produce "beating" in the neutrino type.
For relativistic neutrinos $E = p + m^2/2p$ thus $|E_1 - E_2| \sim |m_1^2 - m_2^2| = \Delta m^2$.

In neutrino oscillations we have measured 2 different Δm^2. Thus neutrinos HAVE MASS although small. Planck 2015 bound is $\Sigma m_\nu < 0.17$ eV (95%).

One way to obtain neutrino masses is to add to the SM new particles called "sterile neutrinos" ν_s. If the lightest of these has a mass $m_s \simeq$ few keV could account for the whole of the DM - would be WDM or "cool DM"

If ν_s are the DM, $\nu_s \to \nu\gamma$ would produce a monochromatic X-ray line in galaxies and galaxy clusters. This line may have been seen at 3.5 keV!

Sterile Neutrinos

The SM has 3 "active neutrinos" with only weak interactions (left-handed neutrinos), but others with no weak interactions (right-handed neutrinos) can be easily added (one or more)

For two-neutrino mixing:
$|\nu_\alpha\rangle = cos\theta\ |\nu_1\rangle + sin\theta\ |\nu_2\rangle$;
$|\nu_s\rangle = -sin\theta\ |\nu_1\rangle + cos\theta\ |\nu_2\rangle$

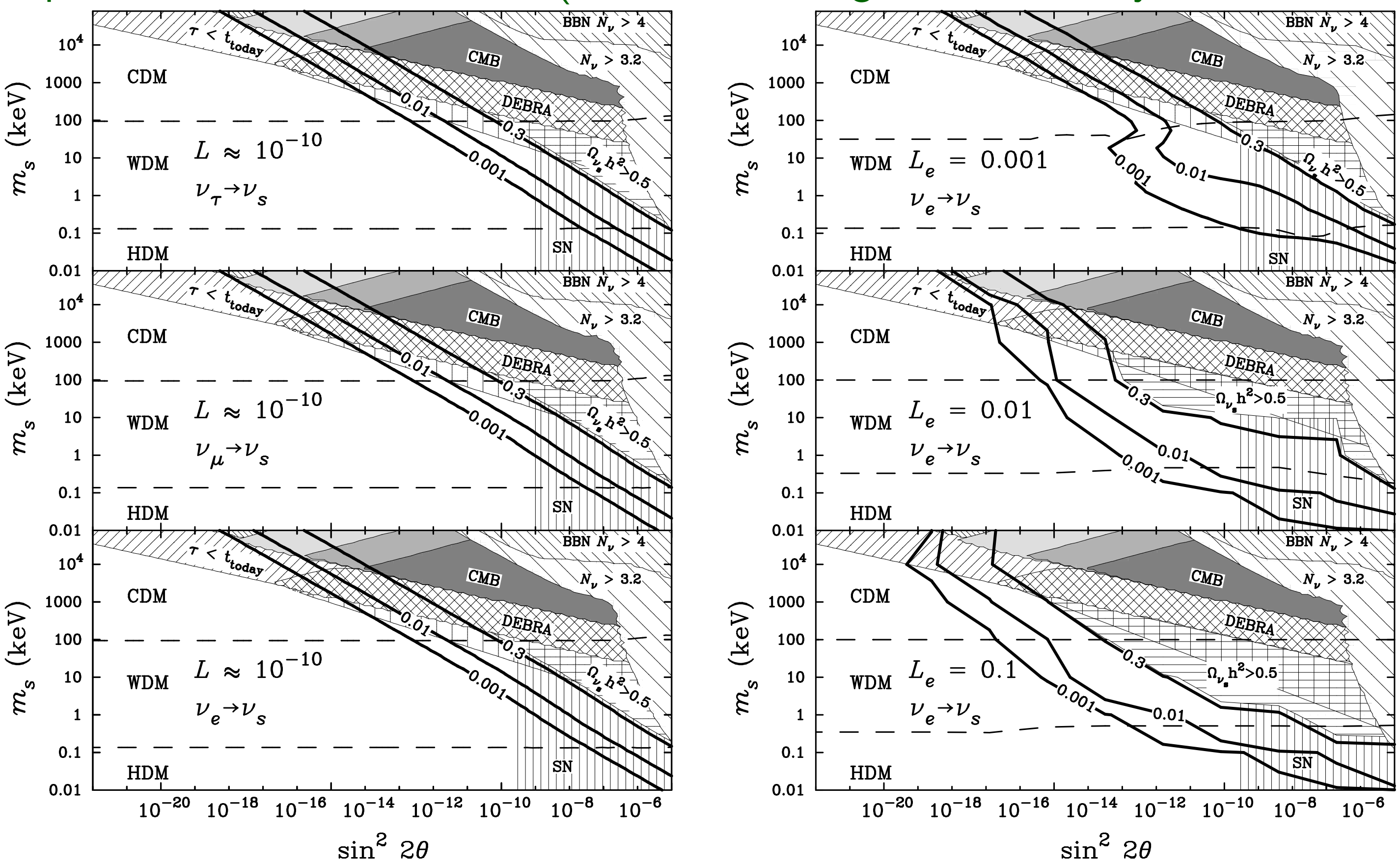
-$|\nu_{\alpha,s}\rangle$: interaction eigenstates (one active or left-handed, one sterile or right-handed)
-$|\nu_{1,2}\rangle$: mass eigenstates, $m_1 << m_2 \equiv m_s$

ν_s can be created via active-sterile oscillations, without (Dodelson & Widrow 1994) or with (Shi & Fuller 1998) a large Lepton Asymmetry L (L-driven MSW conversion), and respectively be Warm DM or "Cool DM" , i.e. "less warm" DM or, alternative, also in the decay of other particles.

Thermal relics of mass $\sim$ keV are becoming non-relativistic at the moment dwarf galaxy core size structures start to form (when $T \sim 1$ keV). Thus they are Warm or "warmish" DM.

Sterile Neutrino Abundance from Abazajian, Fuller, Pattel 2001

$L =$ net lepton number in the Universe (can be much larger than the baryon number $B = 10^{-10}$)



Solid lines indicate density fraction in ν_s 0.3 (whole DM), 0.01, 0.001

An unexplained X ray line found in galaxy clusters

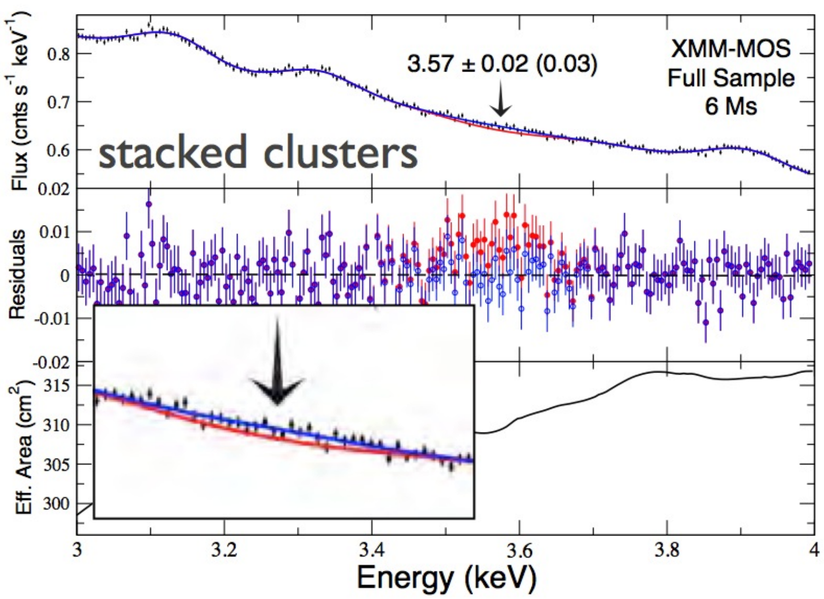
Could be a decaying sterile neutrino

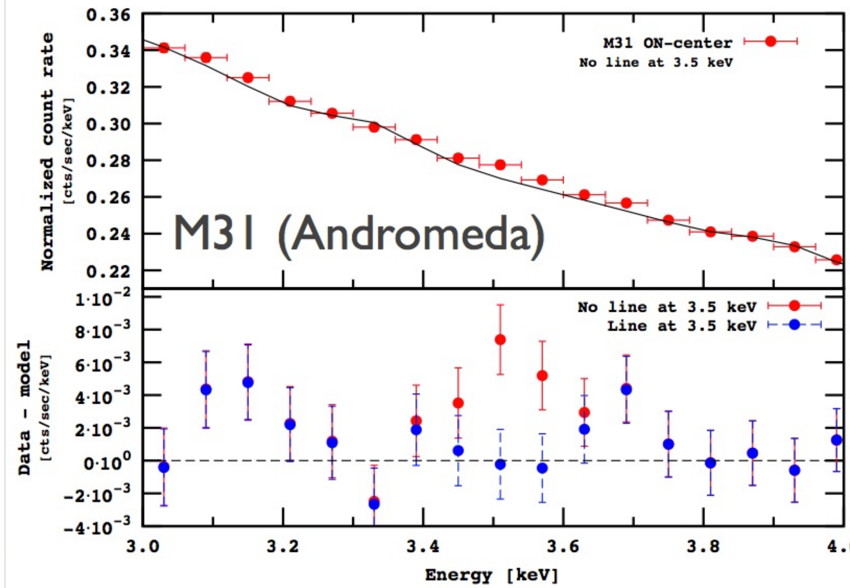
If m_s <1 MeV the lightest sterile neutrino can only decay into an active neutrino and a photon $\nu_s \to \nu\gamma$ (only with $m < m_s$). This is a two-body decay in which each product carries $E_\gamma = m_s/2$

Or "Fluorescent" DM? named by Conlon etal 1608.01684; studied first by Profumo& Sigurdson 0611129, see also D'Eramo etal1603.04859, similar but different from "exciting DM (XDM)" Finkbeiner& Weiner 1402.6671, originally 0702587

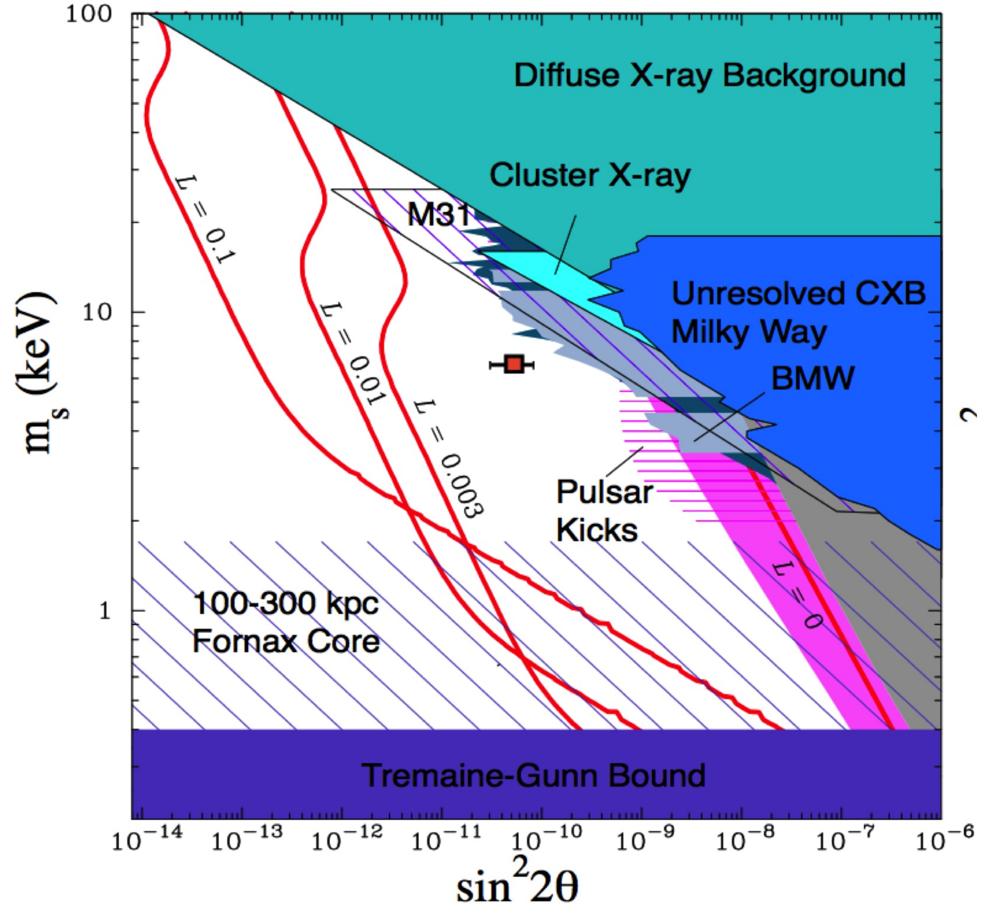
Alternative explanation of the line:
A DM particle χ with mass m_1 can be resonantly excited by absorbing a photon to a state $\chi^{'}$ with mass m_2 and $\chi^{'}$ subsequently de-excites emitting a photon, $\chi^{'} \to \chi\gamma$, with $E_\gamma = E_\gamma^{resonance} = (m_2^2 - m_1^2)/2m_1$.
For $m_\chi^{'} - m_\chi = \delta << m_\chi$, then $E_\gamma \simeq \delta$

A 3.5 keV X ray line found in X-rays from 74 stacked Galaxy Clusters E. Bulbul, M. Markevitch, A. Foster, R. Smith, M. Lowenstein, S. Randall, 1402.2301 and from the Andromeda galaxy and Perseus cluster A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse, 1402.4119.
Could correspond to a 7 keV mass sterile neutrino ($E_\gamma = m_s/2$)
or to Fluorescent DM with ($E_\gamma^{res} = 3.5\text{keV} \simeq \delta$ for $\delta << m$)!



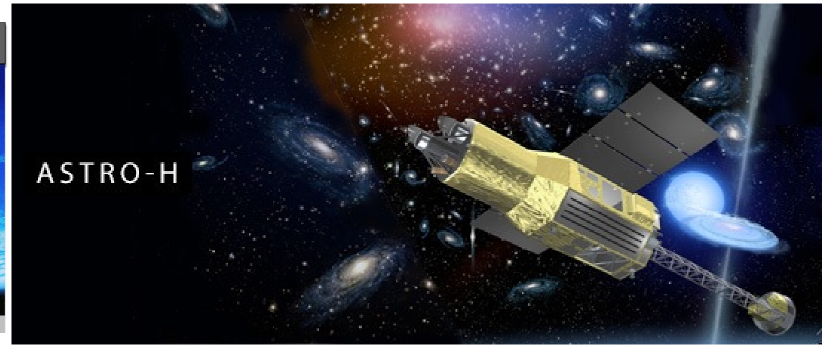


A 7 keV decaying sterile neutrino



* You will estimate the Tremaine-Gunn limit as an exercise

ESA's XMM-Newton & NASA's Chandra do not provide enough energy resolution of the line.



JAXA's ASTRO-H (Hitomi after "first light"), launched on Feb. 17 2016 expected to measure the profile of the line and prove/disprove that it is due to DM in 1 year! was destroyed on March 26. Collected 1 month of extraordinary data on Perseus cluster.

Hitomi coll. 1607.07420: Saw no 3.5 keV line, but signal expected from DM decay scenario too faint to be detected in data Previously reported Perseus core signal was anomalously bright, is rejected at $> 3\sigma$ for broad (DM) line). Inconsistent for ν_s but not conclusive...
Conlon et al 1608.01684 claim results could be consistent with Flurescent DM

(Next planned X-ray astronomy satellite is ESA's ATHENA, scheduled for 2028)

Hitomi and Chandra/XMM-Newton Perseus data compatible for "eXciting" DM (XDM)? Conlon et al 1608.01684

Chandra/XMM-Newton energy resolution∼100 eV, but good angular resolution.

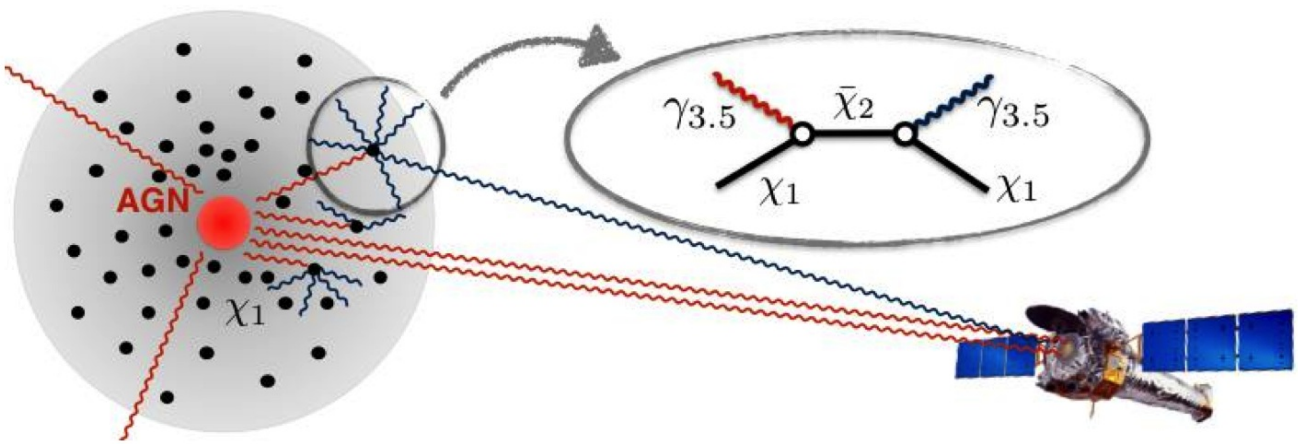
Looked at Perseus data EXCLUDING THE CENTRAL AGN.

Hitomi energy resolution ∼5 eV, observed all the central cluster INCLUDING THE AGN

Chandra 2009 data: AGN spectrum has a dip at 3.5 keV at $> 3\sigma$

(Berg, Conlon et al.1605.01043) where the surrounding region has a line. So both cancel out.

This is possible with "Fluorescent DM" (but not decaying DM) (Fig. from N.Jennings)



Hitomi and Chandra/XMM-Newton Perseus data compatible for "Fluorescent" DM? Conlon et al 1608.01684

Conlon et al proposed "fluorescent DM" whose main property is that total number of 3.5 keV photons is conserved: the total excess emission, integrated across a cluster, must be precisely balanced by the integrated deficit. How would they know without waiting for ATHENA (2018)? They propose:

-The 3.5 keV luminosity has a much sharper central peak for "Fluorescent DM" than for decaying or annihilating DM.

- Anisotropy in the 3.5 keV line strength would indicate FDM.

- Chandra observations of the AGN can be optimized: shorter read-out time, off-axis pointing (and the AGN is twice as luminous as in 2009)